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Residual Strength Calculation & Residual Life Prediction of General Corrosion Pipeline

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Abstract

General corrosion is of the primary reason that causes the pipeline to failure. Researching the residual strength and residual life of general corrosion pipeline is the main measure to conduct the pipeline integrity management, and has great significance to ensure the safety of pipeline transportation. The calculation of the residual strength of even corrosion pipeline under the combined effects of internal pressure and axial force was discussed according to the Tresca yield criterion in elasto-plastic fault mechanics, when the defected size is given, the maximum permissible operating pressure under the defect and the calculation formula for the residual strength of corrosion pipeline are given. On this basis, reliability-based residual life prediction of the corrosion pipeline was developed.

Keywords: Corroded pipeline; General corrosion; Tresca criterion; Residual strength; Residual life .

Nomenclature

D	Inner diameter of pipe	h	Wall thickness of pipe
E_w	Weld coefficient	P	Operation pressure inside the pipelines
F	Axial force in the pipeline section	S	The material allowable stress
η	Design coefficient	σ_s	Minimum yield strength
ν	Poisson ratio	P_{max}	The maximum operation pressure
σ_{Z1}'	The axial stress of pipeline wall under the inner pressure in assumed conditions		
σ_{Z1}''	The axial stress of pipeline wall, under the inner pressure in operation conditions		
σ_{Z1}	The axial stress of pipeline wall under the inner pressure	σ_Z	The axial stress of pipeline
σ_{Z2}	The axial stress of pipeline under the axial load	σ_θ	The hoop stress
P_{hc}	The yield pressure of the current corroded pipeline	$f(\sigma_{ij})$	The stress function in the yield state
P^c_{max}	The allowable maximum working pressure of the axis direction	φ	The safety coefficient
P^θ_{max}	The allowable maximum working pressure of the ring direction	σ_w	The operating pressure of pipeline
σ_{rs}	The residual strength of general corrosion pipeline	$\Phi(\cdot)$	Standard normal distribution function
t	The residual life of general corrosion pipeline		

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1. Introduction

If symbols are used extensively, The oil and gas pipeline always serves in a complicated environment, such as the inner pressure, the axial load and bending load, which causes the pipe to be in a complex stress state [1]. According to the morphological characteristics of the corrosion defects of pipeline, the corrosion defects can be divided into three categories: general corrosion, local corrosion, pitting corrosion [2]. Among which, general corrosion is the primary failure form. So it is very necessary to deduct a deeply research on residual strength and residual life of the oil and gas pipeline, with general corrosion under complex stress state. Oil and gas pipeline always works with high toughness and complex forced situation, therefore, the elastic-plastic behavior of the pipeline must be considered, and conduct analysis based on the elastic-plastic fracture mechanics. The calculation of the residual strength of even corrosion pipeline under the combined effects of internal pressure and axial force was discussed according to the Tresca yield criterion [3] in elasto-plastic fault mechanics, when the defected size is given，the calculation formula for the residual strength of corrosion pipeline are given. On this basis, reliability-based residual life prediction of the corrosion pipeline was developed.

2. The residual strength calculation process and mathe- matical model

2.1. Calculation process

Residual strength is of the ultimate bearing capacity of the structure before the internal crack damage. Residual strength calculation can determine whether the pipeline can meet the safe operation requirements of carrying capacity with the current corrosion state and quantify it, so as to make sure the maintenance and the safety of pipeline under a scientifically supervise. Based on the specification sizes of the oil and gas pipelines and related mechanical model assumptions, residual strength calculation process of general corrosion pipeline are given, as shown in figure 1.

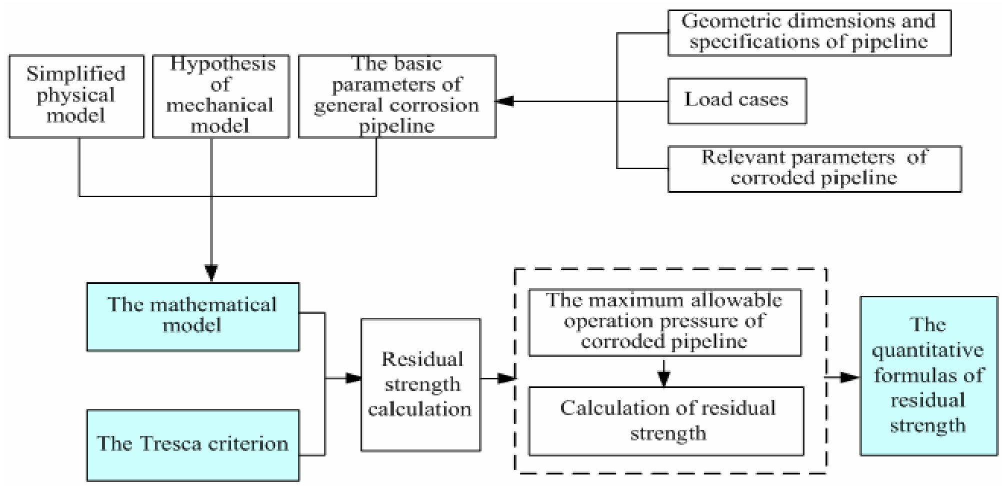

Fig. 1. Residual strength calculation process of general corrosion pipeline.

2.2. The mathematical model of general corrosion pipeline

This paper takes the following hypotheses in conditions of reasonable simplified the actual problem for the convenience of studying problem: ①.Stress hypothesis. The corroded pipeline bears the inner pressure and axial force, which evenly distribute in the respective surface [4]; ②.Condition hypothesis. Corroded pipeline always meets the simple load cases and the Tresca criterion, in the condition of ignoring elastic deformation.

Oil and gas pipeline is infinite long in practical engineering, for the convenience of analysis, a section with general corrosion is picked to conduct a micro-unit analysis, as shown in figure 2(a). The force analysis of the pipeline section is as shown in figure 2 (b)、figure2(c).

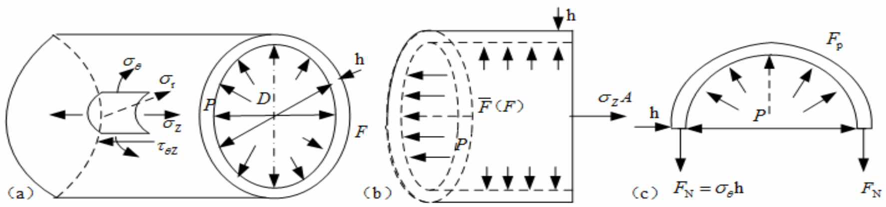

Fig.2. The force analysis of the pipeline section.

The calculation of axial stress should consider the following two aspects:

When the corroded pipeline bears the inner pressure, which is p, it is assumed that the ends of pipeline section are sealed, both ends produced the axial stress in the wall of pipeline under the action of inner pressure. It is known that normal stress distributes evenly in the cross section of the pipeline because of the symmetry of corrosion pipeline, the normal stress can be determined according to the axial tension. According to the figure 2 (b), the axial stress can be given by

$$\sigma_{Z_1}{}' = \frac{\overline{F}}{A} \approx \frac{\mathrm{p} \times \frac{\pi D^2}{4}}{\pi D \mathrm{h}} = \frac{\mathrm{p} D}{4\mathrm{h}} \tag{1}$$

Because of $\mathrm{h} \ll D$, the approximation formula $A \approx \pi D\mathrm{h}$.

In practical engineering, the long-distance buried pipeline can not stretch freely because of the resistance of soil, which causes poisson stress. That the axial stress of pipeline wall also can be given by

$$\sigma_{Z_1}{}'' = \frac{\upsilon \mathrm{p} D}{2\mathrm{h}} \tag{2}$$

By introducing the scalar β, the axial stress can be unified given by

$$\sigma_{Z_1} = \frac{\beta \mathrm{p} D}{4\mathrm{h}} \tag{3}$$

Where $\beta=1$ is in assumed conditions and $\beta=2\upsilon$ is in working conditions.

When the corroded pipeline bears the axial load with size F, according to the theory mechanics, the axial stress produced by pipeline can be given by

$$\sigma_{Z_2} = \frac{F}{\frac{\pi}{4} D^2} \approx \frac{F}{\pi D \mathrm{h}} \tag{4}$$

Because of $\mathrm{h} \ll D$, the approximation formula $\frac{\pi}{4} D^2 \approx \pi D \mathrm{h}$ is utilized in the calculation. Therefore, the total axial stress of pipeline section can be given by

$$\sigma_Z = \sigma_{Z_1} + \sigma_{Z_2} = \frac{\beta \mathrm{p} D}{4\mathrm{h}} + \frac{F}{\pi D \mathrm{h}} \tag{5}$$

In order to calculating the normal stress in the longitudinal section of corroded pipeline, the author intercepted an unit length pipeline, cutting along the longitudinal section, as shown in figure 2 (c). Due to the symmetry of pipeline and $\mathrm{h} \ll D$, the normal stress in longitudinal section distributes even. The resultant force of pressure on the internal surface of the pipeline is F_p=pD. Therefore, the balance equation of the upper part is given by

$$F_\mathrm{p} \text{-} 2F_N = 0 \quad or \;\; \mathrm{p}D - 2\sigma_\theta \times \mathrm{h} \times 1 = 0 \tag{6}$$

According to the balance equation (6), the hoop stress is given by

$$\sigma_\theta = \frac{pD}{2h} \tag{7}$$

3. The residual strength calculation of general corrosion pipeline based on tresca criterion

3.1. The maximum allowable working pressure of the pipeline

It is assumed that corroded pipeline always satisfies simply load condition, considering the condition of uniaxial tension, according to the Tresca criterion of elastic-plastic fracture mechanics [5], the stress state is $\sigma_1=\sigma_s$ and $\sigma_2=\sigma_3=0$ (σ_1, σ_2 and σ_3 are the three principal stress of the yield point), the Tresca yield condition is $k_1=\sigma_s/2$, where k_1 is material constant. The yield pressure is equal in the condition of both ends open and close when it meets the Tresca yield criterion. So, the corroded pipeline can be equivalently considered as the uniaxial tension and closed pipeline in calculating the maximum working pressure.

The simplified mechanical system is shown in figure 2 (a). Because of $h \ll D$, stress in the middle of the pipeline section, which is away from both ends, is supposed to be uniform distribution [6]. Usually the hoop stress is larger than axial stress, namely $\sigma_\theta \geq \sigma_z$, so we can deduce $\sigma_1=\sigma_\theta$, $\sigma_2=\sigma_Z$ and $\sigma_3=\sigma_r=0$. If the current wall thickness of general corrosion pipeline is h_c, the current stress state of corroded pipeline is $\sigma_z=\frac{pD}{4h_c}$, $\sigma_\theta=\frac{pD}{2h_c}$, $\sigma_r=0$, $\tau_{Zr}=\tau_{r\theta}=\tau_{\theta Z}=0$ (where σ_r is the radial stress, τ_{Zr}, $\tau_{r\theta}$ and $\tau_{\theta Z}$ are the corresponding shear stress). According to the Tresca criterion, the material enters the yield state when maximum shear stress access to its limit state. So we can deduce the equation between the material constants and the principal stress:

$$f(\sigma_{ij})=\frac{\sigma_1-\sigma_3}{2}-k_1=0 \tag{8}$$

Substituting $\sigma_1-\sigma_3=\sigma_\theta=\frac{pD}{2h_c}$ into the equation (13), we can deduce the yield pressure of pipeline by the given wall thickness of the defect.

$$p_{h_c}=\frac{2\sigma_s h_c}{D} \tag{9}$$

According to the theory of elastic-plastic fracture mechanics and the relevant criteria, and the defect size of corrosion pipeline, the allowable maximum working pressure of the axis direction is given by

$$P_{max}^{Z}=\frac{4SE_w\left(h_c-F/\pi SE_w D\right)}{\beta D} \tag{10}$$

The allowable maximum working pressure of the ring direction is given by

$$P_{max}^{\theta}=\frac{2SE_w h_c}{D} \tag{11}$$

The allowable maximum working pressure of the pipelines is given by

$$P_{max}=\min\left(P_{max}^{C}, P_{max}^{L}, p_{h_c}\right) \tag{12}$$

3.2. The calculation on residual strength of corrosion pipeline

Because the allowable maximum security working pressure of pipeline qualitatively responses the ultimate bearing capacity of pipeline, the residual strength pipeline can be quantified by the allowed maximum working pressure of corrosion pipeline. So the residual strength of general corrosion pipeline can be given by

$$\sigma_{rs} \approx \varphi P_{max} = \varphi \min\left(\frac{2SE_w h_c}{D}, \frac{4SE_w\left(h_c - F/\pi SE_w D\right)}{\beta D}, \frac{2\sigma_s h_c}{D}\right) \tag{13}$$

4. The residual life prediction of general corrosion pipe based on reliability theory

4.1. The reliability-based life prediction model of corrosion pipeline

If residual strength of the pipeline is greater than operating pressure of material in operation period, the pipeline operation failure will not occur during the period, the limit state function is given by

$$Z=\sigma_{rs}-\sigma_w \tag{14}$$

For the limit state function as above type, within a running time t, when $Z>0$, the pipeline failure does not occur; when $Z<0$, the pipeline failure occurs. Therefore, in a certain value t, the probability of $Z>0$ is the reliability of life period t. If residual strength is lower than the operating pressure, the pipeline failure occurs.

Failure probability P_f and reliability $R(t)$ are given by

$$P_f = P(\sigma_{rs} \le \sigma_w) = P(\sigma_{rs}-\sigma_w \le 0) = P(Z \le 0) \tag{15}$$

$$R(t) = P(\sigma_{rs} > \sigma_w) = P(\sigma_{rs}-\sigma_w > 0) = P(Z<0) \tag{16}$$

4.2. The reliability-based residual life prediction of corrosion pipeline

As can be seen from the reliability assessment model, the key of getting general corrosion pipeline reliability is to determine the distribution of the operation pressure and residual strength. Through the tubing mechanical performance testing and pipe blasting experiment data analysis, it shows that they both have approximate normal distribution [7].

As long as get operating pressure data of general corrosion pipeline at a different time, the distribution parameters can be calculated and the value of μ and σ can be determine.

Due to $\sigma_w \sim N(\mu,\sigma^2)$, according to the properties of the normal distribution, $Z=\frac{\sigma_w-\mu}{\sigma}$ Obeys the standard normal distribution $N(0,1)$. The reliability also can be given by

$$R(t) = P(\sigma_w < \sigma_{rs}) = P\left(\frac{\sigma_w-\mu}{\sigma} < \frac{\sigma_{rs}-\mu}{\sigma}\right) = \Phi\left(\frac{\sigma_{rs}-\mu}{\sigma}\right) \tag{17}$$

Then the failure reliability of pipeline life is given by

$$R(t)=\Phi\left(\frac{\sigma_{rs}-\mu}{\sigma}\right) = \Phi\left(\frac{\varphi \min\left(\frac{2SE_w h_c}{D}, \frac{4SE_w\left(h_c - F/\pi SE_w D\right)}{\beta D}, \frac{2\sigma_s h_c}{D}\right)-\mu}{\sigma}\right) \tag{18}$$

In the case of having h_c 、μ 、σ , the reliability can be got by looking up the standard normal integral table.

Under a certain temperature, the empirical formula [8] between stress and fracture time is given by

$$t=A\sigma^{-B} \tag{19}$$

where A and B are parameters. In the calculation, test data which is obtained through the pipe specimen tensile test have a processing on the least square method, the value of A and B can be determined. So the residual life of general corrosion pipeline under the defect is given by

$$t=A\left[\varphi \min\left(\frac{2SE_{\mathrm{w}}\mathrm{h}_{\mathrm{c}}}{D}, \frac{4SE_{\mathrm{w}}\left(\mathrm{h}_{\mathrm{c}}-F/\pi SE_{\mathrm{w}}D\right)}{\beta D}, \frac{2\sigma_{\mathrm{s}}\mathrm{h}_{\mathrm{c}}}{D}\right)\right]^{-B} \tag{20}$$

So the reliability of general corrosion pipeline continue running t under the given defect size is $R(t)$.

5. Conclusion

Residual strength of the long-distance oil and gas pipeline mainly depends on the situation around, and general corrosion is the primary failure form of pipeline. In practical projects, pipelines in service are with different degree of corrosion. In order to ensure the safety of the pipeline, minimize the economic losses caused by various possible accidents, the research on residual strength and residual life of general corrosion pipeline should be developed. The calculation of the residual strength of even corrosion pipeline was discussed according to the Tresca yield criterion in elasto-plastic fault mechanics, combining with the maximum operating pressure, the calculation formula for the residual strength of corrosion pipeline are given, on this basis, reliability-based residual life prediction of the corrosion pipeline was developed.

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